Pulsed Power Processing and rf Gradient Limits

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Main Arguments

- The same mechanisms now seem to determine the future of all major HEP projects.: ILC, CLIC, Muon Collider, Neutrino Factory.
- The details of these mechanisms are not being actively studied.
- We have developed a model of breakdown and gradient limits in normal rf systems.
- We extend this model to SCRF systems.
- New experiments can understand and improve SC gradient limits.

Contributions from:

Part of the Neutrino Factory and Muon Collider Collaboration - Muon Cooling

- Experiments in Fermilab MuCool Test Area (MTA) , aimed at MICE

  J. Norem, Argonne

  A. Moretti, A. Bross, Z. Qian, B. Norris, FNAL

  Y. Torun, D. Huang IIT

  D. Li, M. Zisman, S Virostek LBNL

  R. Rimmer, JLab

  R. Johnson, P. Hanlet, et. al, Muons Inc.

  + many others

- Modeling of breakdown and cavity parameters

  Z. Insepov, A. Hassanein, ANL

- Surface studies with Atom Probe Tomography at Northwestern Univ.

  D. Seidman, K. Yoon, NW Univ.

- Plasma modeling (B and gas effects)

  P. Stoltz, Tech-X Corp.

Bibliography

Major papers:

- Open Cell Cavity, Phys. Rev. STAB **6**, 072001 (2003)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.6.072001
  Measurements of 6 cell cavity, dark current measurements, w/wo B fields, comp. with other cavities, tensile stress

- Cluster emission, Phys. Rev. STAB **7**, 122001 (2004)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.7.122001
  Emission of clusters, thermal and field dependence,

- Breakdown mechanics, Nucl. Instrum. and Meth A **537**, 510, (2005)
  http://www-mucool.fnal.gov/mcnotes/public/pdf/muc0286/muc0286.pdf
  General theory of tensile stress triggered breakdown

- Magnetic fields, Phys. Rev. STAB **8**, 072001 (2005)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.8.072001
  Measurements with 805 MHz pillbox, measurement of $s_2(\beta)$

- Surface damage, Phys. Rev. STAB **9**, 062001 (2006)
  http://link.aps.org/doi/10.1103/PhysRevSTAB.9.062001
  Relationship between surface damage and maximum operating fields.

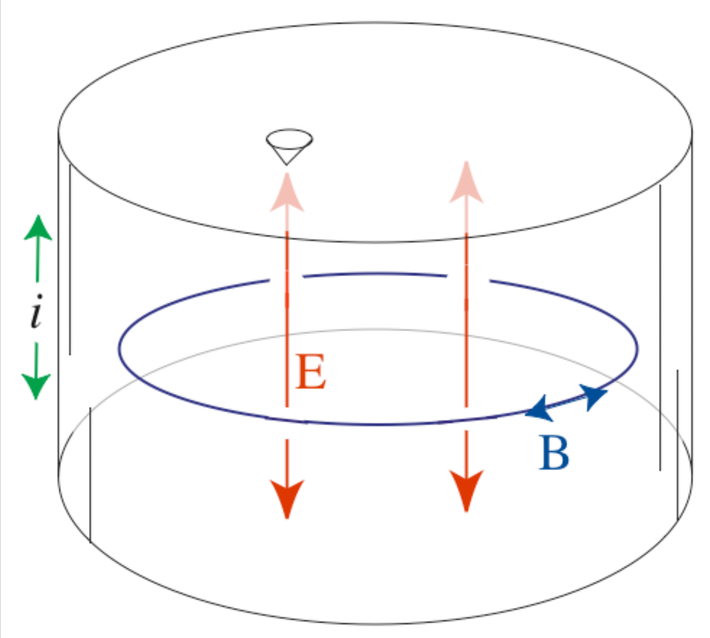
Structures seem to fail in similar ways.

Normal metals

- Stresses from electric fields exceed material tensile strength.
  $E \sim 7$ GV/m

Superconductors*

- Field emission heats cavity before tensile stress limit.
  $E \sim 4$ GV/m



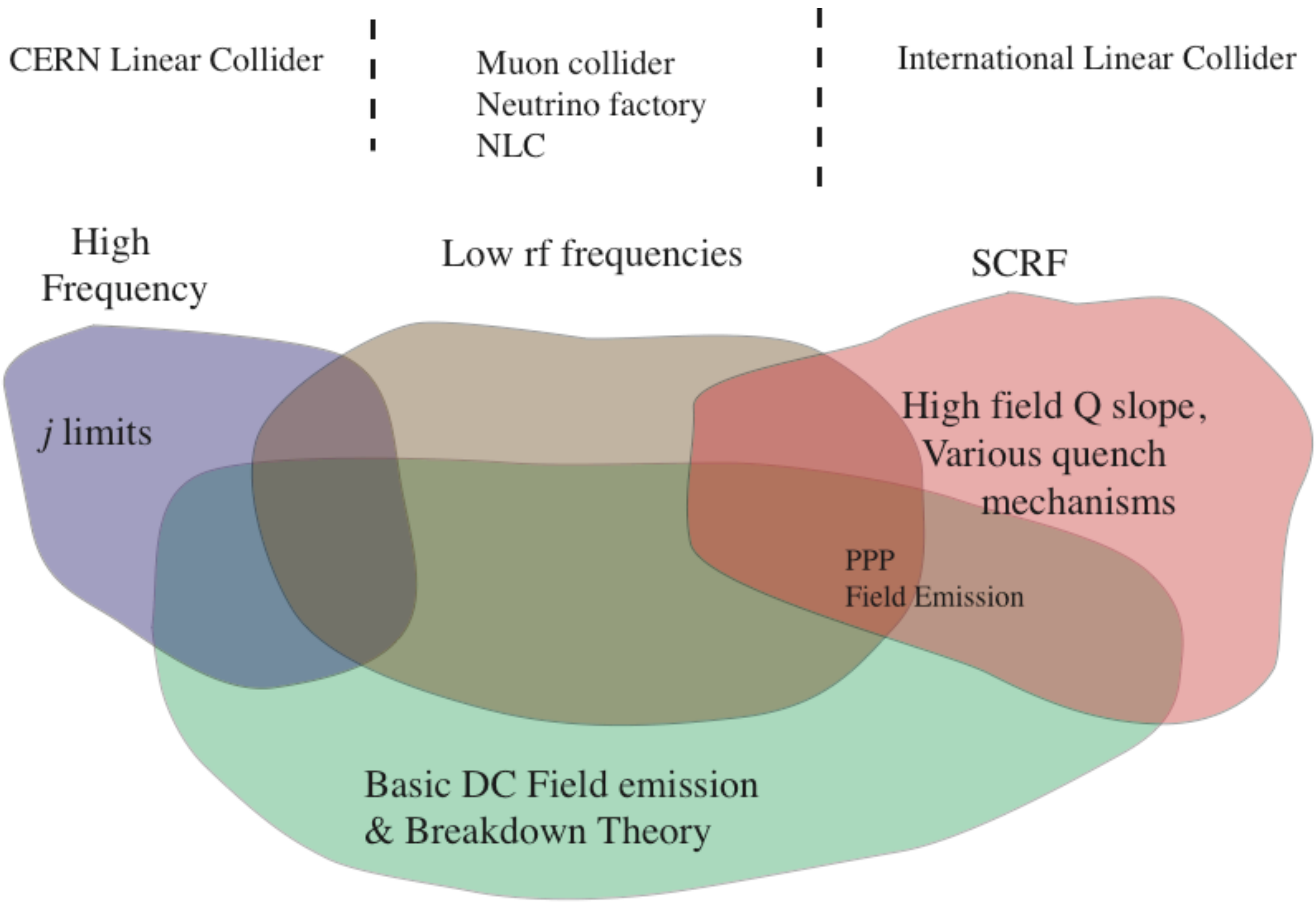
- Skin currents damage walls.
  $\Delta T \sim 100^0$

- $B > H_{c1}$, material goes normal
  $B \sim 180$ mT

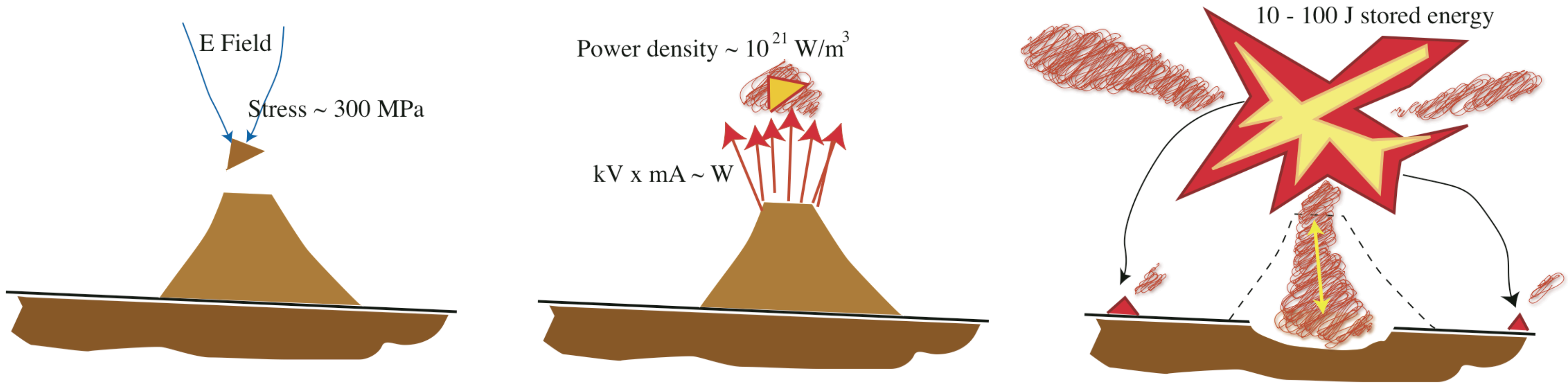
* other mechanisms are active

How does this affect SCRF operation?

- Normal breakdown theory seems to determine much SCRF behavior.



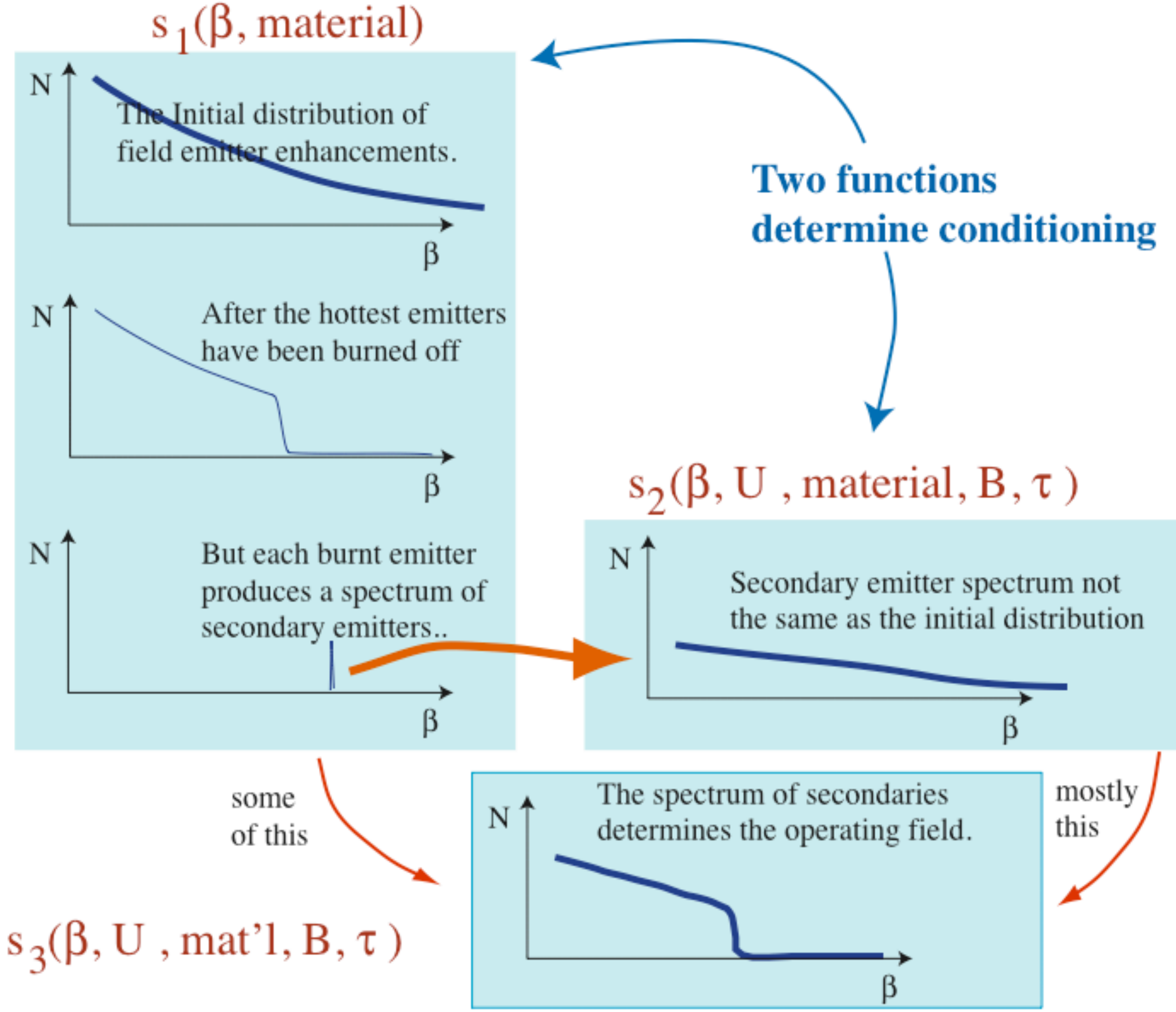
Our model of breakdown in normal systems



Fracture is the trigger	Field emission produces plasma	Lossy plasma absorbs energy
$\varepsilon_0 E^2/2 = T$	$dE/dx = \{\ \}/\beta^2$	$s_2(\beta) = \exp(-b\beta)$

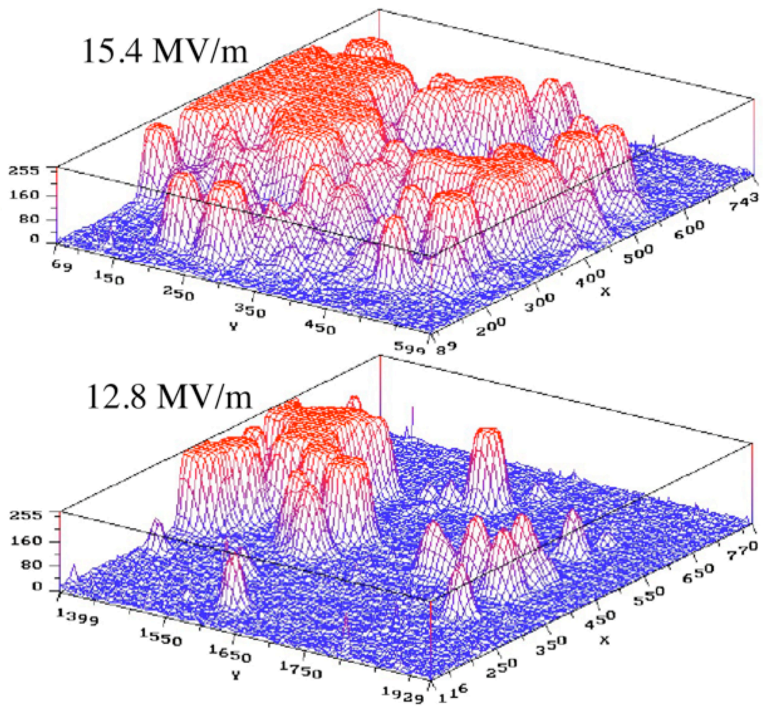
- Field emission is a diagnostic.
- An equilibrium state develops between the structure and the surface.
- Things depend on the available energy, U.

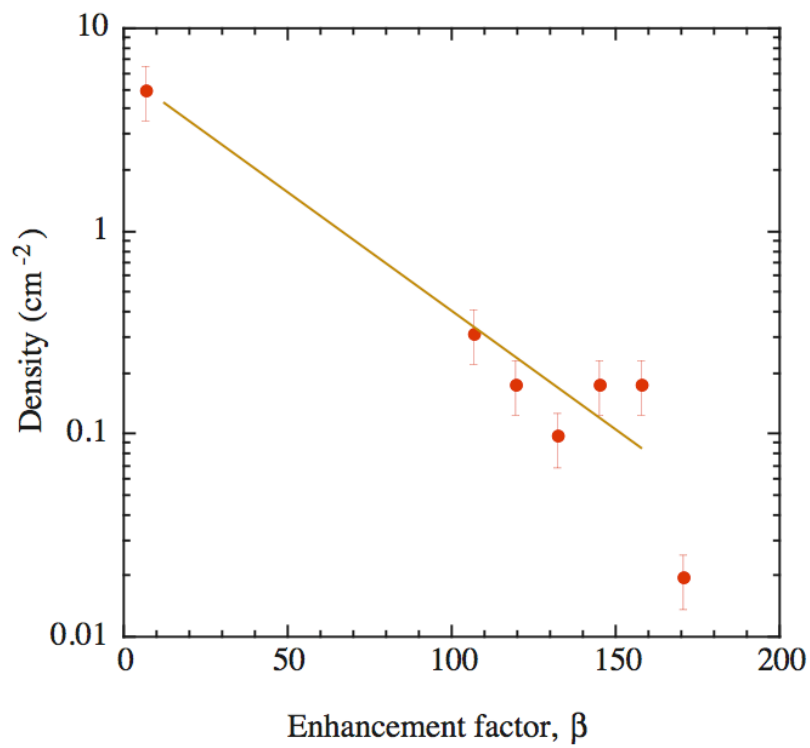
Spectra of field emitters (enhancement factors)



We have measured $s_2(\beta)$, during operation, with a Be window.

- We looked at individual emitters, and measured spectra produced in discharges





- The spectrum of enhancements seems to be a "Maxwell-Boltzmann" like exponential.

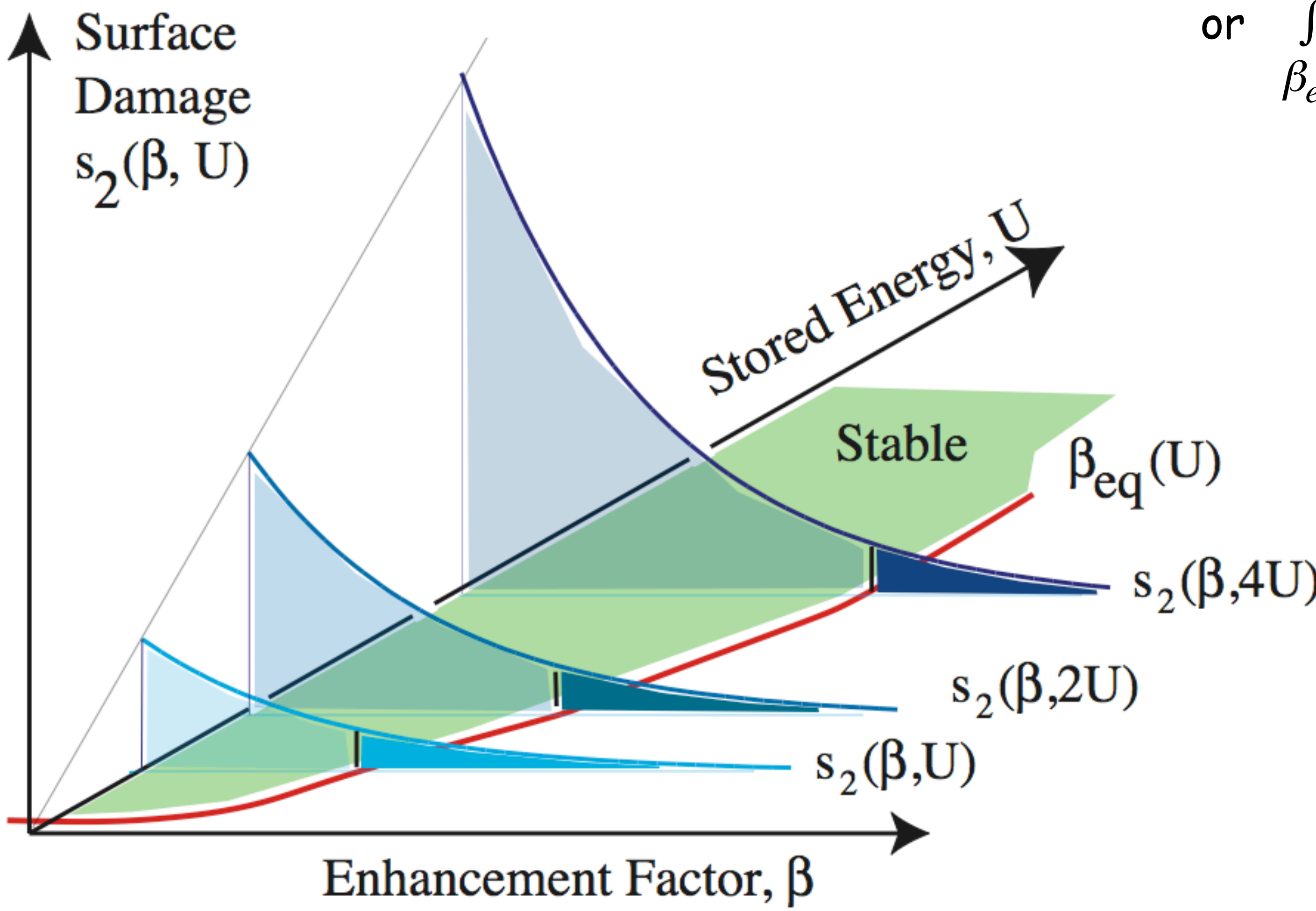
- We assume the spectrum is proportional to the energy in the discharge, U.

Calculating $\beta(U)$ gives the maximum operating field.

- **Stable operation demands that:**

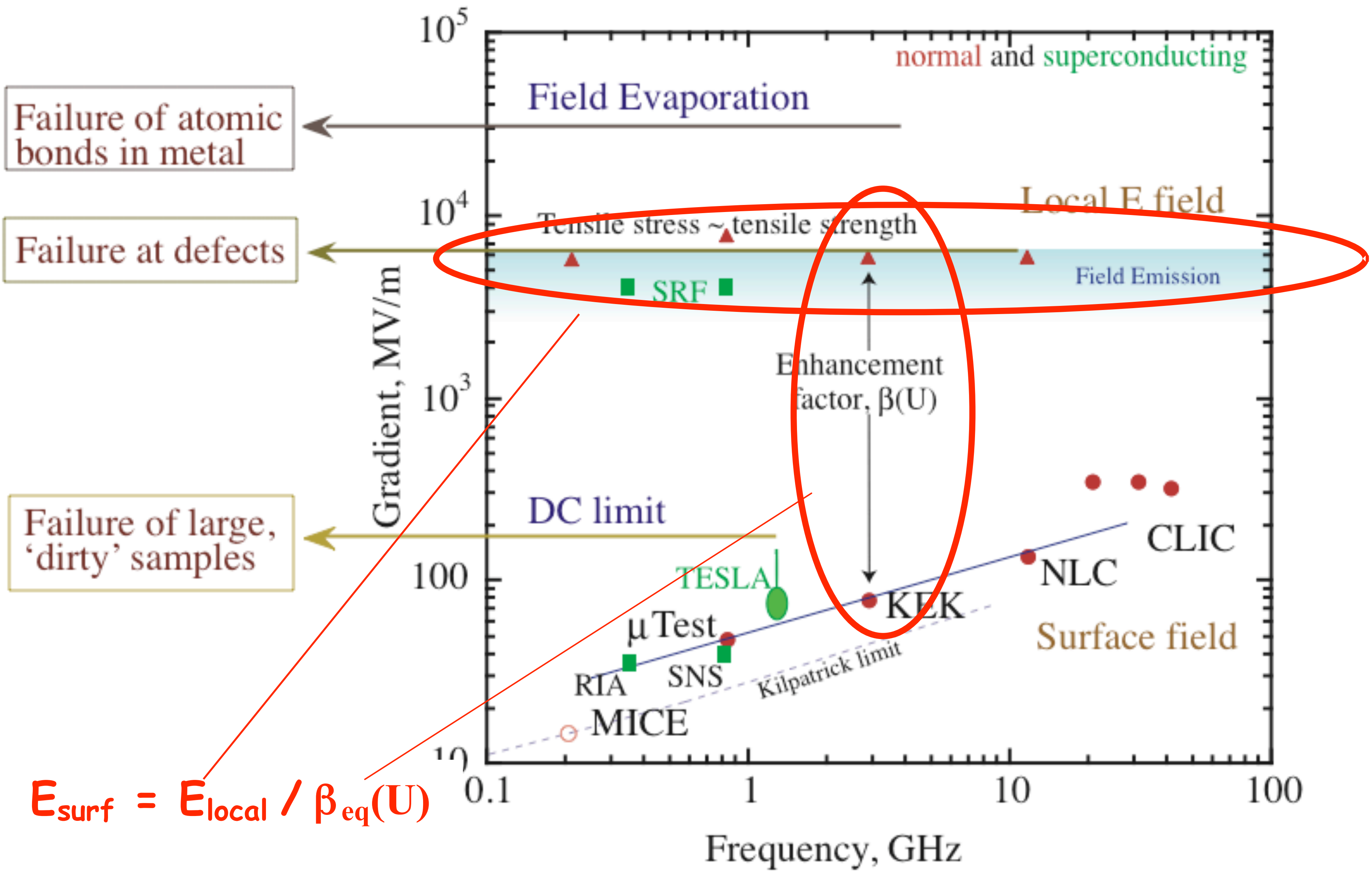
  Breakdown events cannot create more damage than they destroy.

or $\int_{\beta_{eq}}^{\infty} s_2(\beta, U) < 1$



The Model: Local fields + enhancements determine everything.

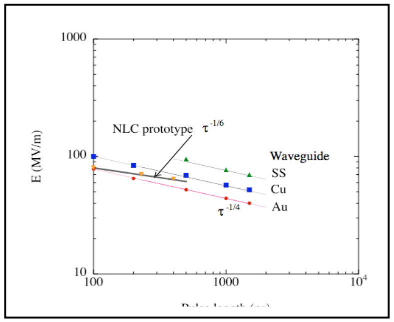
- If we know E_{local}, and can calculate β, we can determine rf limits.



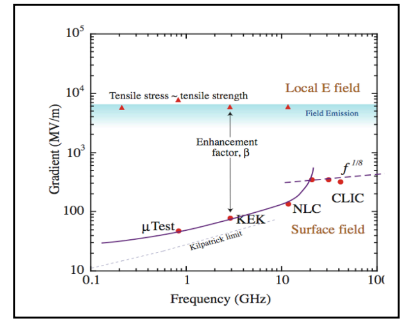
$E_{surf} = E_{local} / \beta_{eq}(U)$

We can calculate all aspects normal rf operation.

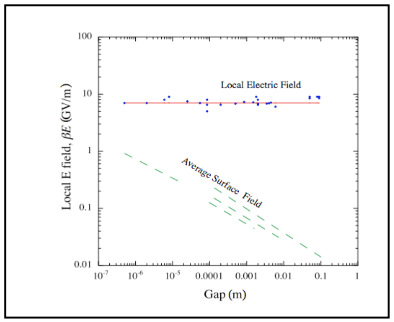
- Emax vs. Pulse Len.



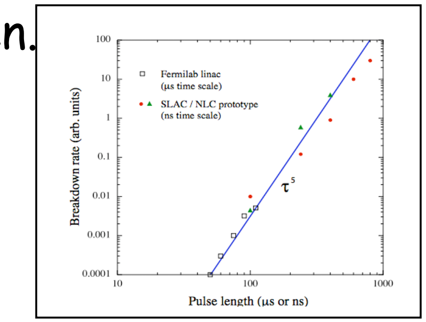
- Emax vs. f



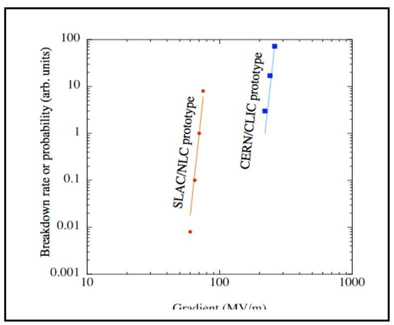
- DC breakdown



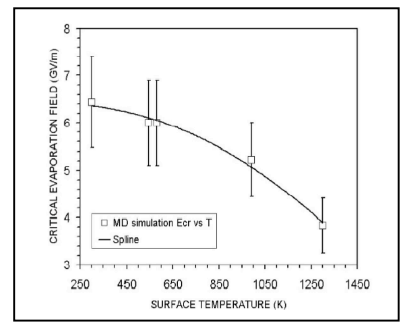
- BD rate vs. Pulse len.



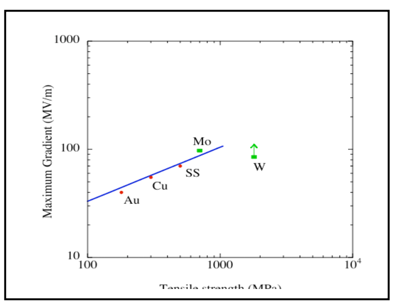
- BD rate vs. E



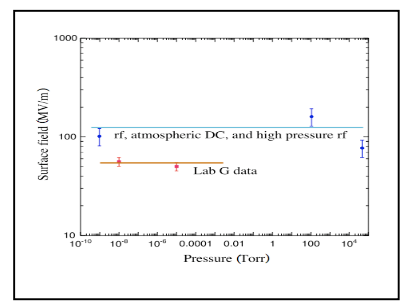
- Emax vs. T



- Material dep.



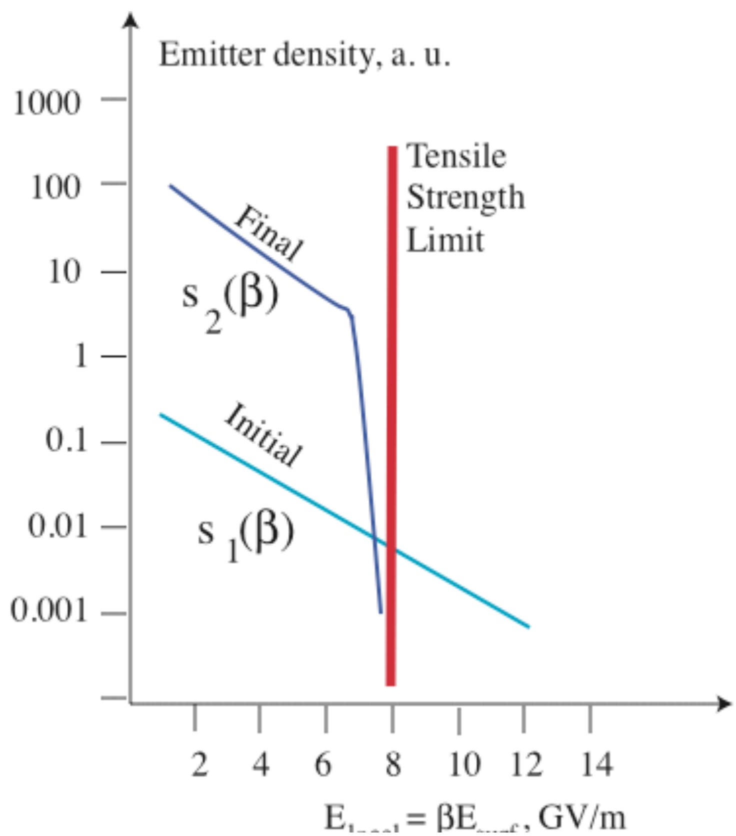
- E_{max} vs. pressure



Similarities and differences.

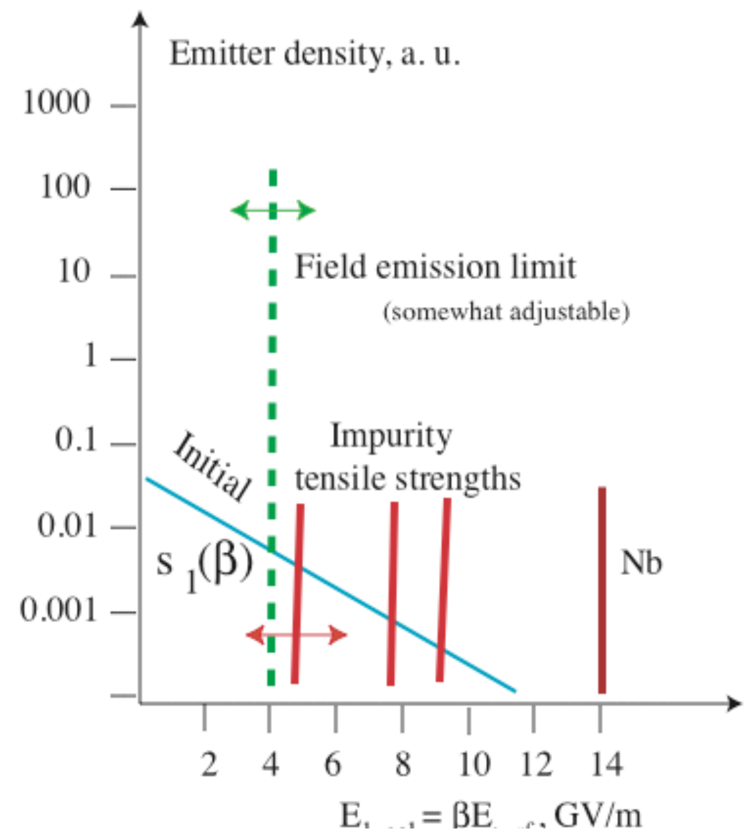
Normal conductors

- Fracture determines gradients
- Power thru field emission
- Copper fractures @ ~8 GV/m
- Copper is pure, ~monolayer oxide
- $s_2(\beta)$ (secondary dist.) gives limits



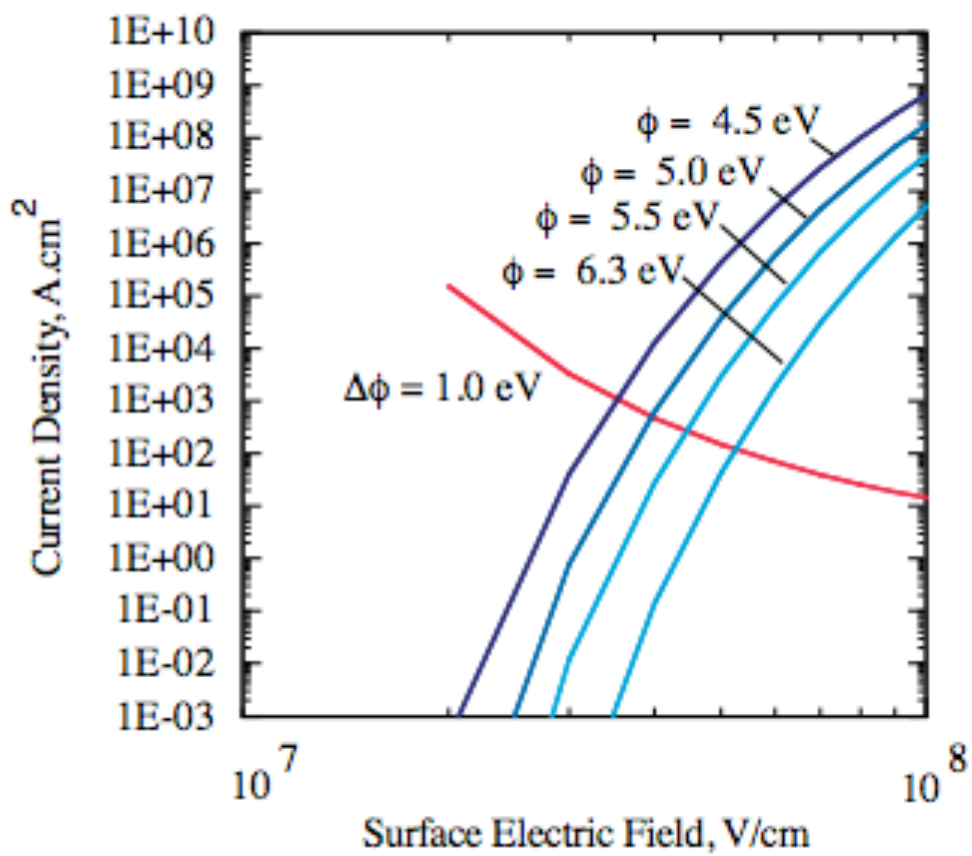
Superconducting rf

- Field emission determines gradients
- Stopped by FE at 4 GV/m
- Nb fractures @ ~14 GV/m
- Contamination particles, oxides ??
- Initial conditions $s_1(\beta)$ give limit
- Field emission limit can be moved.



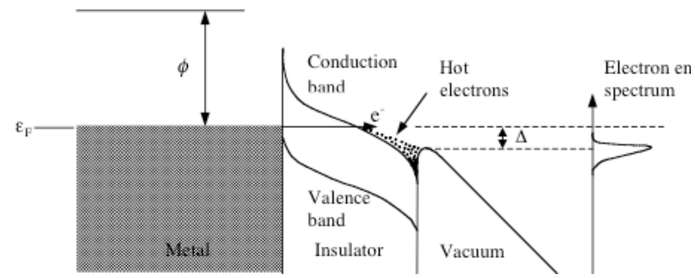
Changing the surface changes field emission.

- Monolayers do it.
- Improvements of 30 - 50% seem possible.
- What is the initial state?



More data needed on field emitters / breakdown sites,

- What are the properties and effects of oxides on field emitters?
  - Resistive heating?
  - Tunneling (Metal-Insulator-Vacuum model)?
  - Do they pop off under mechanical stress?
  - Current carrying Filaments thru insulators?
  - Switching properties?
  - Will coatings stick?

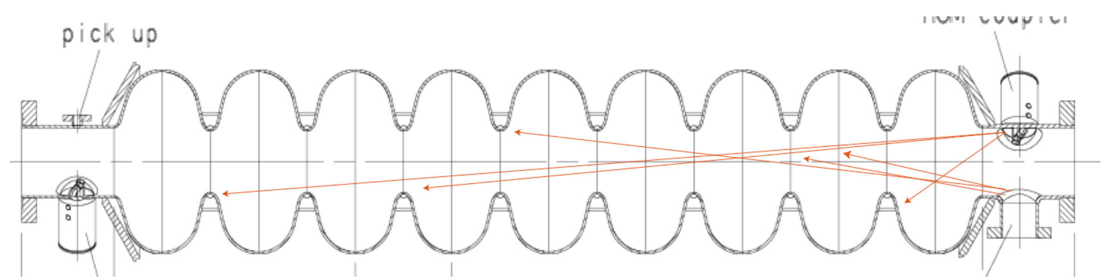


- Need data on the work functions of Nb, and impurities, with realistic surfaces.

. . . and ways to minimize field emission in situ.

- Test monolayer deposition of high ϕ materials on these surfaces.

- Develop system for *in-situ* monolayer deposition of these materials.



Summary

- We have a new model of breakdown and gradient limits in normal rf.
- Applying this model to SCRF systems gives some insight to field emission, Pulsed Power Processing and SCRF gradient limits from field emission.
- Field emission may prevent reaching the surface fields where PPP works.
- It may still be possible to coat the interior surface with monolayers of high ϕ materials to suppress Field Emission and perhaps gain 20 - 50 % in gradient.
- This environment can be understood using Atom Probe Tomography technology.

Measuring field emission.